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Mangroves and coral reefs: David Stoddart and the Cambridge physiographic tradition

Colin D. Woodroffe
University of Wollongong, colin@uow.edu.au

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Abstract
Mangroves are particularly extensive on sheltered, macrotidal, muddy tropical coastlines, but also occur in association with coral reefs. Reefs attenuate wave energy, in some locations enabling the accretion of fine calcareous sediments which in turn favour establishment of seagrasses and mangroves. Knowledge of the distribution and ecology of both reefs and mangroves increased in the first half of the 20th century. J Alfred Steers participated in the Great Barrier Reef Expedition in 1928, and developed an interest in the geomorphological processes by which islands had formed in this setting. It became clear that many mangrove forests showed a zonation of species and some researchers inferred successional changes, even implying that reefs might transition through a mangrove stage, ultimately forming land. Valentine Chapman studied the ecology of mangroves, and Steers and Chapman described West Indian mangrove islands in the 1940s during the University of Cambridge expedition to Jamaica. These studies provided the background for David Stoddart's participation in the Cambridge Expedition to British Honduras and his PhD examination of three Caribbean atolls. One of these, Turneffe Islands, is an atypical atoll, with mangroves occupying more than 25% of the reef platform. In contrast to this atoll-like island, there are other island types on the Belize barrier reef, including similar extensive mangrove islands called 'ranges'. Stoddart compared the more complex of these, comprising shingle ridges and sand cays around which the mangroves occur, with the 'low wooded islands' on the Great Barrier Reef. Many of those that he had mapped were devastated by Hurricane Hattie in 1961, and the opportunity to revisit these, and document the storm damage and subsequent recovery, led to much important evidence for the role of storms in the long-term evolution of both reefs and reef islands. In 1973, Stoddart led the Royal Society and Universities of Queensland Expedition to the northern Great Barrier Reef. During this extensive period of fieldwork, Stoddart and colleagues remapped Low Isles in detail, the best-known of the low wooded islands, and many other islands in less detail. The contrast between islands on the Belize coast with those on the Great Barrier Reef provided many insights into the geomorphology of both reefs and the vegetation of islands that form on them. The physiography of the islands provided many clues to the way they had formed and the processes operating. It became clear to Stoddart that there has been a different sea-level history in these two locations. He was able to observe and infer the response of key habitats to tropical cyclones (hurricanes). In many cases island physiography differs between individual islands, reflecting a broader suite of factors such as inherited topography and morphodynamic feedbacks; in other cases, mangrove establishment appears to have been opportunistic. Subsequent studies have elucidated the stratigraphy and geochronology in some locations; in many cases confirming the hypotheses that Stoddart proposed. His insightful descriptions and meticulous fieldwork have provided a wealth of observational data that have inspired subsequent studies and that will continue to generate alternative hypotheses that future environmental scientists can endeavour to test.

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MANGROVES AND CORAL REEFS: DAVID STODDART AND THE CAMBRIDGE PHYSIOGRAPHIC TRADITION

COLIN D. WOODROFFE[1]

ABSTRACT

Mangroves are particularly extensive on sheltered, macrotidal, muddy tropical coastlines, but also occur in association with coral reefs. Reefs attenuate wave energy, in some locations enabling the accretion of fine calcareous sediments which in turn favour establishment of seagrasses and mangroves. Knowledge of the distribution and ecology of both reefs and mangroves increased in the first half of the 20th century. J Alfred Steers participated in the Great Barrier Reef Expedition in 1928, and developed an interest in the geomorphological processes by which islands had formed in this setting. It became clear that many mangrove forests showed a zonation of species and some researchers inferred successional changes, even implying that reefs might transition through a mangrove stage, ultimately forming land. Valentine Chapman studied the ecology of mangroves, and Steers and Chapman described West Indian mangrove islands in the 1940s during the University of Cambridge expedition to Jamaica. These studies provided the background for David Stoddart's participation in the Cambridge Expedition to British Honduras and his PhD examination of three Caribbean atolls. One of these, Turneffe Islands, is an atypical atoll, with mangroves occupying more than 25% of the reef platform. In contrast to this atoll-like island, there are other island types on the Belize barrier reef, including similar extensive mangrove islands called 'ranges'. Stoddart compared the more complex of these, comprising shingle ridges and sand cays around which the mangroves occur, with the 'low wooded islands' on the Great Barrier Reef. Many of those that he had mapped were devastated by Hurricane Hattie in 1961, and the opportunity to revisit these, and document the storm damage and subsequent recovery, led to much important evidence for the role of storms in the long-term evolution of both reefs and reef islands. In 1973, Stoddart led the Royal Society and Universities of Queensland Expedition to the northern Great Barrier Reef. During this extensive period of fieldwork, Stoddart and colleagues remapped Low Isles in detail, the best-known of the low wooded islands, and many other islands in less detail. The contrast between islands on the Belize coast with those on the Great Barrier Reef provided many insights into the geomorphology of both reefs and the vegetation of islands that form on them. The physiography of the islands provided many clues to the way they had formed and the processes operating. It became clear to Stoddart that there has been a different sea-level history in these two locations. He was able to observe and infer the response of key habitats to tropical cyclones (hurricanes). In many cases island physiography differs between individual islands, reflecting a broader suite of factors such as inherited topography and morphodynamic feedbacks; in other cases, mangrove establishment appears to have been opportunistic. Subsequent studies have elucidated the stratigraphy and geochronology in some locations; in many cases confirming the hypotheses that Stoddart proposed. His insightful descriptions and meticulous fieldwork have provided a wealth of observational data that have inspired subsequent studies and that will continue to generate alternative hypotheses that future environmental scientists can endeavour to test.

INTRODUCTION

Mangroves grow throughout much of the tropics, extending into subtropical and temperate regions along the eastern margins of continents. Mangrove forests are particularly extensive where low gradient plains have developed in areas of considerable tidal range. Muddy estuarine and deltaic

[1] School of Earth and Environmental Sciences, University of Wollongong, NSW 2522, Australia. colin@uow.edu.au

environments associated with the mouths of major rivers support extensive mangrove forests. However, mangroves can also flourish in association with coral reefs. This overview focuses on the occurrence and development of mangroves in relation to reefs, and reconsiders the significant contributions to their study made by David R. Stoddart.

Mangroves, corals and seagrass have co-occurred in shallow tropical seas since the evolution of their constituent taxa in the Cretaceous (McCoy and Heck, 1976). It has become clear that there are interconnections between the ecosystems each support (Mumby, 2006; Harborne et al., 2006; Olds et al., 2013), and interdependencies between these three communities (Saunders et al., 2014; Guannel et al., 2016). Some naturalists have hypothesised that there might be a succession of ecosystems with reefs preparing the way for seagrass, and mangroves subsequently vegetating reef platforms, culminating in the development of islands (Welch, 1963). The role of mangroves in this context intrigued Stoddart, and he investigated this directly both in Belize and on the Great Barrier Reef. His insights stimulated further research in other reef settings. This paper reconsiders these contributions.

MANGROVE FORESTS AND THEIR OCCURRENCE: EARLY IDEAS

Where several species grow in mangrove forests, they have often been observed to be forming nearly monospecific zones parallel to the shore. The zonation of mangroves led to the concept that there is a temporal succession. One of the most detailed descriptions of the occurrence of the numerous mangrove species within well-developed mangrove forests was on the Malayan Peninsula by Watson (1928). In his monograph, Watson remarked that boundaries between mangrove species were often remarkably distinct, and he related their occurrence to elevation within the tidal frame and the consequent frequency of inundation by tides. However, he recognised that there were 'influencing factors besides the frequency of inundation being drainage, the character of the soil, the age of the swamp, the erosive or accresive [sic] action of the sea, and the artificial conditions brought about by exploitation' (Watson, 1928, p.133). He considered that there was a pattern of development of the mangrove communities, which he called types, with *Avicennia* and *Sonneratia* being pioneers on accreting coasts, whereas *Bruguiera gymnorhiza* marked the final stage typical of the transition from littoral to inland forest. Such patterning is a generalisation and not all types are represented even in extensive swamps, nor do all mangrove forests inevitably pass through the entire sequence of development (Watson, 1928, p.149).

Also in 1928, William Morris Davis produced a detailed synthesis of what he termed, the *Coral Reef Problem*, reviewing the physiography of coral reefs, reinforcing the evolutionary perspective of reef types propounded by Charles Darwin. Coincidentally in the same year, the Great Barrier Reef Expedition commenced a year-long exploration of the Great Barrier Reef in northeastern Australia. Led by C. Maurice Yonge, the expedition adopted Low Isles, 10 km northeast of Port Douglas, as its headquarters. Since its early recognition by Cook in 1770, and subsequent description by King in 1819 and MacGillivray in 1848, Low Isles had been referred to as a *low wooded island*, because of the extensive mangroves covering part of the reef top. The expedition was primarily concerned with the 'elucidation of problems which have a direct bearing on ecology (i.e. towards a study of conditions and food-supply in the sea, of feeding and metabolism of corals, of the growth and breeding of marine organisms and so forth)' (Stephenson et al., 1931, p.19). As a component of the expedition, the Royal Geographical Society sponsored J. Alfred Steers of the University of Cambridge to visit Queensland. Steers, a physical geographer, took an interest in the variability of reef islands along the reef (Steers, 1929, 1931). He made use of a 'physiographic sketch map' compiled using a plane-table survey by E.C. Marchant, which outlined the major features of the reef top. Mangroves were not a particularly prominent component of the 1928−1929 Great Barrier Reef Expedition itself; however, it was possible to discriminate near continuous areas of mangrove swamp composed primarily of *Rhizophora* from more open canopies referred to as mangrove park on many of the reef platforms within the inner reef. Particularly significant was a detailed map of Low Isles augmenting the plane-table survey by theodolite triangulation and comparison with aerial photography, prepared by Spender (1930). This was initially used as a base map for the ecological studies, but has since provided a basis for examining geomorphological changes at Low Isles (Hamylton, 2017). The description by Steers (1929), and the mapping by Spender (1930), of Low Isles, had provided an introductory examination of a key island type. Steers called these ‘low wooded islands’, and his more extensive visit to the Queensland coast in 1936 allowed him to visit and map many more of these complex island types (Steers and Kemp, 1937).

The capacity of *Rhizophora* to disperse across the ocean had been documented by Guppy (1906), and the viviparous nature of its propagules had been described in detail by Bowman (1917). Observation of seedlings established in shallow water and the cohorts of saplings that can eventuate, together with the tendency for zonation, gave rise to the view that one mangrove species ‘prepares the way’ for another (Banijbatana, 1958; Kuenzler, 1974). For the mangrove zones to be part of a temporal sequence there would need to be a mechanism by which one species facilitated replacement by the next, and this was postulated to be the vertical accretion of the surface of the substrate. Slowing of water movement within the above-ground root systems of mangroves, whether stilt-like prop roots or peg-like pneumatophores, was considered to lead to increased sediment deposition. Accretion reduces the frequency of inundation and was believed to trigger species change (Chapman, 1944; Fosberg, 1966). In this way, mangroves had been considered by some to be ‘makers of land’ (Vaughan, 1909) and even ‘trees that walk to the sea’ (Hodge, 1956).

WEST INDIAN MANGROVES

Mangrove forests in the West Indies are composed of three principal mangrove species, the red mangrove *Rhizophora mangle*, the black mangrove *Avicennia germinans* and the white mangrove *Langucularia racemosa*. Of these, *Rhizophora* is almost always found on the seaward margin with the other mangroves behind, implying a simple zonation. Valentine Chapman synthesised the distribution of mangroves throughout the tropics in his book, *Mangrove Vegetation* (Chapman, 1976). His early work had been on the mangroves of Jamaica. In 1939, while at Gonville and Caius College, he had led the University of Cambridge expedition to Jamaica. Here he had worked with Steers mapping the cays on the southern coast, particularly those in Portland Bight and Kingston Harbour. Whereas Steers described the physiography of several of the reef islands in Port Royal, Portland Bight and elsewhere around Jamaica (Steers, 1940a, 1940b), Chapman focused on the ecology of the mangroves. Chapman stressed that whereas the distribution of mangroves may be climatically determined, ‘there is also a physiographic element in their formation’ (Chapman, 1944, p. 427).

The dichotomy between reef mangroves and mud mangroves had been identified for some time. However, on the University of Cambridge expedition to Jamaica, Chapman and Steers mapped and described a variety of islands associated with the coral reefs. They discovered that mangroves also grew on sand, particularly calcareous sand of reefal origin in which the alga *Halimeda* was a conspicuous component (Steers, 1940a; Steers et al., 1940). It was clear that mangrove seedlings had established sporadically amid coral boulders on several of the islands, or in particularly sheltered leeward shores on small cays. In these situations there was little evidence to support mangroves building land; ‘the presence of mangrove is more a matter of chance arrival and the establishment of a seedling’ (Chapman, 1976, p. 9). Steers (and Lofthouse) mapped Pigeon Island in Portland Bight, an island partially surrounded by shingle and partially by sand, with mangroves fringing a lagoon in the centre. He compared this, and nearby Salt Island, with the low wooded islands of the Great Barrier Reef, although stressing that there was not a prominent conglomerate platform (which he called a promenade) in the Jamaican case (Steers, 1940a).

Also significant was the situation where the mangrove forest, particularly along the Palisadoes of Port Royal near Kingston, was underlain by peat. Chapman described this, saying:

> ‘This marine peat develops only in areas where there is very little or no supply of silt in the water, and in these circumstances it is very clear that the mangroves, particularly the Black [*Avicennia*] and White [*Laguncularia*], are bringing about the formation of new land by a process entirely different from that normally ascribed to them. The usual

> method is by the mechanical trapping of silt, but here it is the actual accumulation of the roots of the plants that is responsible for the development of the new land. So far as is known this is a hitherto undescribed method. The peat is extremely firm, the swamps are readily traversed, and one large area of this type of mangrove swamp is being cleared to form an aerodrome. The formation of new land by this means is much slower than by the trapping of silt. For this reason such swamps show very little change in outline when successive maps are compared' (Steers et al., 1940, p. 320).

In the same year, 1940, and noted in a footnote to the Steers et al. paper, J.H. Davis published one of the most important and influential studies on the geomorphological role of mangroves looking at mangroves and the peat deposits beneath them in southwest Florida. Davis recognised a zonation from seawardmost *Rhizophora mangle* to more landward *Avicennia germinans* in the mangroves of Florida, and interpreted this patterning to indicate a temporal sequence of communities culminating in a climax vegetation of tropical forest. Examining the stratigraphy of mangroves and using aerial surveys, Davis inferred considerable accretionary ability within the *Rhizophora*, which he envisaged to be prograding over the marine shoals of Florida and Biscayne Bays. He indicated that 'if new, mature swamp areas are considered land, then there are more than a thousand acres of recently formed land in the Florida Bay to Biscayne Bay region'. (Davis, 1940, p. 408).

TURNEFFE ISLANDS

The Turneffe Islands comprise particularly extensive mangrove forests. It is now a conservation area (Turneffe Atoll Management Plan, 2012). The atoll is valued for its populations of manatee, turtles, lobster and conch; it is important as one of the few remaining nesting sites for the American crocodile, and there is tarpon (*Megalops atlanticus*), permit (*Trachinotus falcatus*) and bonefish (*Albula vulpes*) fishing. Although there are no settlements directly on the atoll, there are privately owned properties and a resort as well as educational facilities (Calabash Cay, University of Belize Environment Research Institute, and Blackbird Cay, Oceanic Society).

David Stoddart's PhD through the University of Cambridge considered the offshore reefs to the east of the Belize barrier reef. Entitled *Three Caribbean atolls: Turneffe Islands, Lighthouse Reef, and Glovers Reef, British Honduras*, it was published in 1962 as *Atoll Research Bulletin* no. 87 (and also available through the Louisiana State University Coastal Studies Institute, as contribution no 62-3, being the seventh part of the eleventh in a series of reports obtained under project Nonr 1575(03), Task Order No NR 388 002 of the Geography Branch of Naval Research). Of the three atolls, Turneffe Islands are composed of particularly extensive mangrove forests, and is therefore a focus for more detailed description in this overview.

The study formed a part of a broader description of the cays of Belize (then known as British Honduras), undertaken from the University of Cambridge as part of the Cambridge Expedition to British Honduras, 1959–1960, led by John Thorpe. David Stoddart joined the expedition as a geographer, although he subsequently jested that he 'knew not a single thing about any of the plants and animals, both terrestrial and marine' (Stoddart, 2001, p. 243). Aboard a vessel called the *Tortuga*, the members visited much of the barrier reef and its islands, as well as the outlying atolls. These islands were poorly understood, few had been described since they were charted by the British hydrographer Richard Owen in the 1830s (Figure 1). Coincidentally, they had also been the object of preliminary study by Don Vermeer from the Department of Geography at Berkeley (Vermeer, 1959). Vermeer had classified the cays of the reef into i) sand cays, ii) mangrove cays, and iii) mangrove-sand cays, which he regarded as a transition type. Stoddart followed this broad classification, and recognised that 'one might say that Turneffe is really one large mangrove-sand cay' (Stoddart, 1962a, p. 116).

The Turneffe Islands are a reef platform with an area of 525 km^2 (Figure 2). Mangroves are particularly extensive, much of the perimeter of Turneffe Islands is fringed with mangrove islands

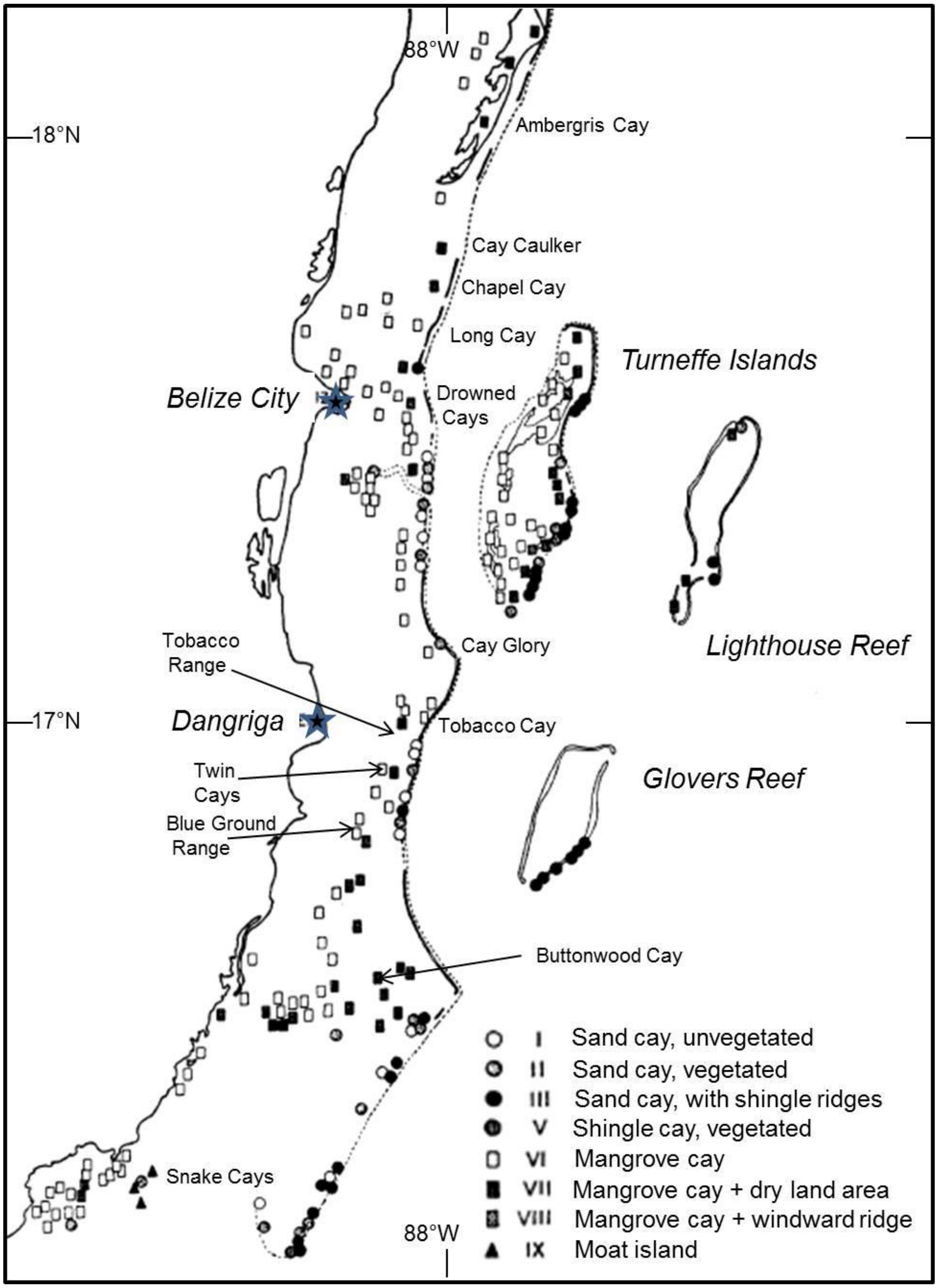

Figure 1. The Belize Barrier Reef, showing the location of the three Caribbean atolls, Turneffe Islands, Lighthouse Reef and Glovers Reef, that Stoddart described for his PhD, and his classification of other island types along the length of the reef (after Stoddart, 1965).

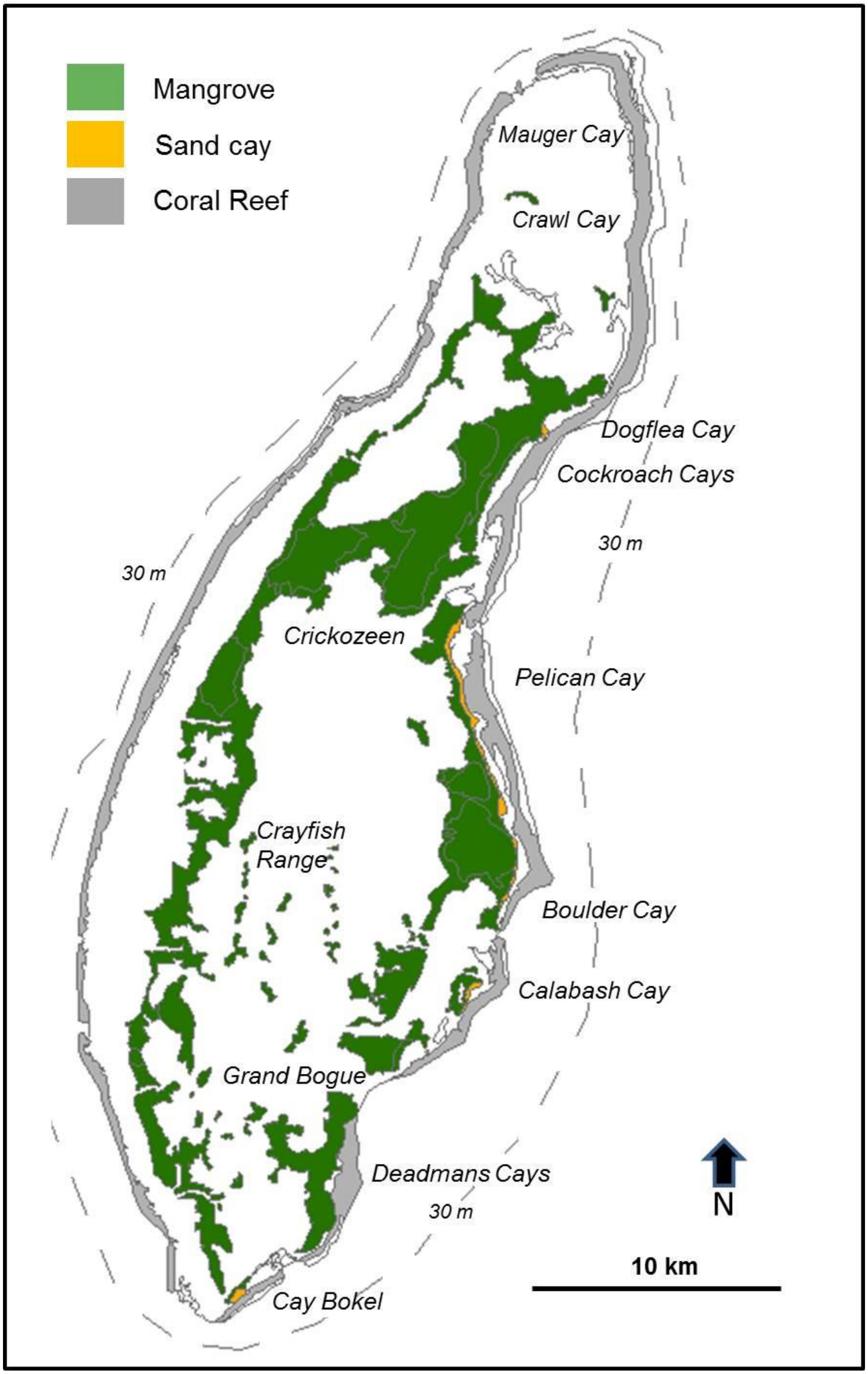

Figure 2. Turneffe Islands, on which mangroves, primarily *Rhizophora mangle*, occupy more than 25% of the reef platform (mapping following Meerman, 2006).

covering >25% of the platform area. A sponge industry flourished on Turneffe in the early 1900s, but collapsed in the 1930s, and has only been intermittently restored. Although termed an atoll, in his 1962 thesis Stoddart recognized that the presence and distribution of mangroves on this atoll-like reef appeared to be almost unique, as nothing quite comparable had been described in the literature (Stoddart, 1962a, p.127). He concluded that the reef did not really fall into the stricter definition of an atoll. Turneffe is relatively sheltered behind Lighthouse Reef from the prevailing northeast trade winds for most of the year, but may be exposed to 'northers', high pressure fronts moving down from the north, and occasional hurricanes from April to October. The region is microtidal, with tidal range around 50cm. From Mauger Cay in the north to Cay Bokel in the south, Turneffe Atoll is 50 km long. The eastern reef rim consists of a reef crest with *Acropora palmata* and *Orbicella (Montastraea) annularis* prominent on the reef front. Islands occur intermittently along this eastern rim; small sandy islands make up Deadmans Cays in the south and Dogflea and Cockroach Cays in the north. Behind these tiny sandy cays, a more continuous line of mangrove occurs, interrupted by Northern Bogue to the north, Grand Bogue in the southeast, and several smaller channels also called bogues at various other places along this margin. The mangrove fringe on the eastern margin, reaching more than 3 km wide in places, is relatively exposed, and a discontinuous sand and shingle ridge has formed from reefal sediments swept across the reef flat. This is up to 200 m wide and rises about 1–2 m above the reef flat. It supports coconuts in places, but is elsewhere covered by strand vegetation.

The eastern cays on Turneffe were among the first islands surveyed, and the sand cays were examined in greater detail than the extensive mangrove islands. Whereas sand cays were surveyed by pace and compass, mangrove islands:

> 'present special problems and cannot be surveyed to the same standards as dry land areas. Where mangrove zones on sand cays are less than 100 yards long the traverse was normally carried to seaward of them, but this was liable to disruption by deepening water, softening bottoms, and inquisitive sharks and barracuda.' (Stoddart, 1962a, p.129).

The western reef rim of Turneffe is still lower in terms of wave energy, and much of the reef crest does not reach the sea surface. Instead, the reef front has a cover of gorgonians and the corals *Orbicella (Montastraea)*, *Diploria* and the branching *Acropora cervicornis,* in contrast to *Acropora palmata* which characterises higher energy reef settings around these atolls. There is then a broad shelving backreef floor, with a cover of the seagrass *Thalassia testudinum* (and also *Syringodium filiforme*), until the fairly continuous mangrove fringe that occurs between 600 m and 3km lagoonward of the reef crest. The mangrove fringe is more continuous than on the eastern margin, with 4 or 5 much narrower channels connecting into the central lagoons. A northern lagoon is almost enclosed by mangrove and was not visited by Stoddart, whereas the Central Lagoon (which he called Southern lagoon) and the more open southern lagoon, are accessible through numerous bogues. The lagoons are about 2–3 m deep, reaching a maximum of 8 m deep; circulation is restricted and temperatures can reach 30°C and salinities of up to 42.5‰ (Gischler, 2003). There are several channels between the mangrove islands and these are scoured by tides. They have a muddy floor, with seagrass and *Halimeda*. Within the lagoon are small mangrove islands, composed predominantly of the red mangrove, *Rhizophora mangle*, most rising fairly abruptly from the lagoon floor.

HURRICANE HATTIE

Shortly after Stoddart had completed mapping of the cays of Belize, one of the most devastating hurricanes to hit the region passed across Turneffe Islands and the barrier reef. It provided the opportunity to revisit and remap islands. The account of the damage and subsequent recovery represents one of the best documented studies of these phenomena in any reef environment (Stoddart, 1962b, 1963, 1969, 1971).

Stoddart had identified damage to the mangroves that he attributed to hurricanes in his early studies, but their role was starkly demonstrated by the passage of Hurricane Hattie on 30–31 October 1961. The storm, a Category 5 hurricane on the Saffir-Simpson scale, went right over Turneffe and had intense winds of 240 km/h with gusts of more than 320 km/h (Stoddart, 1963). The eye of the hurricane appears to have passed over Pelican Cay on Turneffe around midnight (Stoddart, 1963, p. 11). Within a few months of the storm, Stoddart re-surveyed cays he had mapped in 1960. The most severe damage was experienced along a 40-km wide track; the storm surge reached 4.2 m high at Cay Caulker, increasing to 6 m at the mainland coast (Stoddart, 1963).

The larger islands survived better than the smaller ones, and those with a protective ridge to their windward fared better than those without. Damage to mangroves included extensive mortality and defoliation; mechanical damage, stem breakage and erosion of substrates were apparent. Greater damage was recorded on cays that had been disturbed by human interference. In the zone of maximum damage, where the storm surge had been greatest, mangroves were exposed to inundation and wave action. There were areas where trees were felled by the wind, falling in a range of directions rather than just one single direction. On Turneffe, damage was greatest to mangroves on the eastern margin of the atoll; almost all were defoliated, though some interior protected areas remained with leaves. Stoddart inferred that wave action played a major role in stripping the leaves. Regrowth of leaves on some trees was already apparent in 1962, but others remained without leaves in 1965 and were evidently killed as a result of passage of the hurricane. Mangroves on Crayfish Range and adjacent islands in the centre of Turneffe were largely defoliated, whereas only those on the eastern margin of islands to the west of the atoll lost their leaves. The considerable volumes of water driven into the lagoon by the surge, resulted in scouring of channels through the mangroves on the western margin, with oversteepening of banks and scouring of sediment from the floor, causing deposition of sandy deltas at their western exit. Stoddart described dislocation of blocks of mangrove substrate adjacent to Crickozeen Creek on the west, in what he inferred to have been rotational slumping (Stoddart, 1963). Many of the areas had not recovered by 1965, although the overall perimeter of mangrove occurrence changed little after the storm, for example at Cockroach cays (Stoddart, 1969).

MANGROVE ISLANDS OF THE BELIZE BARRIER REEF

Stoddart mapped, and re-mapped, the numerous cays on the Belize barrier reef and within the lagoon (Figure 1). In 1982, he extended an earlier classification (that distinguished 9 types of island, (Stoddart, 1965; see Figure 1) to recognise the following 11 types of island (Stoddart et al., 1982): i) unvegetated sand cay, ii) vegetated sand cay, iii) unvegetated shingle cay, iv) vegetated shingle cay, v) sand and shingle cay, vi) mangrove cay, vii) shelf islands, viii) mangrove cay with dry sand areas, ix) mangrove range, x) moat islands, and xi) coastal barrier islands (which occur along the mainland coast and originate as a part of beach processes on that coast, such as cuspate foreland formation, rather than being directly associated with the reef).

Mangrove cays had been recognised by Vermeer (1959), and occur within the lagoon and not on the outer barrier reef itself. His category of mangrove-sand islands contains the class mangrove cay with dry sand areas, which comprise particularly those many islands dominated by mangrove but on which a sand ridge accretes on the windward side, as typified for the eastern margin of Turneffe Islands. Shelf islands are a relatively restricted category that are outlined by Ebanks on the shallow shelf north of Belize City, formed ‘by sediment accretion on a partly submerged topographic prominence’ (Ebanks, 1975, p.277). The term ‘mangrove range’ describes the extensive and more complex elliptical islands of dense mangrove, with numerous interior lagoons or meandering creeks. The term ‘moat islands’ was applied by Stoddart to several islands formed on patch reefs in the southern lagoon, which comprise a windward shingle ridge, shallow reef-top lagoon, interior mangrove swamp, and leeward sand cay. The islands had a moat, a slightly deeper section of the reef surface, and he noted analogies between these and the ‘low wooded islands’ on the Great Barrier Reef (Stoddart, 1965). Plants of the larger mangrove islands on which there are sandy or shingle ridges are distinctive from vegetation of sand cays on the reef edge, with many more grasses, sedges and succulents (Stoddart et al., 1982, p.67).

Mangrove islands are absent from exposed reef flats, being found only in the lagoon, where they may have shingle or sand ridges on the windward side in some cases, but in lower energy settings may be just mangrove (Stoddart, 1965). Peat accumulates beneath mangroves, particularly *Rhizophora*, but some sediment may be accreting onto these islands to form the ridges where they are exposed to sufficient energy. Vermeer (1959) had hypothesised that ridges had formed when the sea level had been higher, but Stoddart was able to dispel this idea, postulating instead that:

> ‘this general energy model represents the fundamental control of cay types, the presence or absence of islands depending largely on the existence of a geometrically suitable foundation at a suitable depth at any point in the energy spectrum’ (Stoddart, 1965, p. 142).

Under these circumstances, the nature of the island and the extent of mangroves on them depended on the variability and strength of wind, effective fetch, depth of water to windward, and local factors of reef depth and geometry, and was not a response to changes of sea level.

In the northern lagoon, Stoddart described numerous large mangrove islands between Cay Chapel and Belize City (17°30′N to 17°45′N). Long Cay and the northernmost of the Drowned Cays comprised mangrove-sand cays with a narrow windward sand ridge on which coconuts grow, whereas the remainder (Hicks Cays, Montego and Frenchman’s Cays, Hen and Chicken Cays and Rider’s Cays) consist entirely of mangrove (Stoddart et al., 1982). Many of these islands are dissected by deep meandering channels flushed by strong tidal currents. The larger east-west channels are called bogues. Similar mangrove islands occur at the inner margin of the Belize Deepwater Channel, such as Grennel’s Cay and One Man Cay.

Within the central lagoon, the lagoon floor increases in depth from the mainland to depths of 20–24 m, and with a reef rim, or barrier platform, 5–8 km wide and 4–6 m deep. Mangrove islands occur on the inner margin of this barrier platform; most are linear cays oriented north-south, and lack windward sand ridges. South of 17°N these mangrove islands become larger and more complex, several are elliptical in shape and are known as mangrove ranges.

Tobacco Range is an elliptical array of mangrove islands about 4.8 km long and 1.8 km wide, and has a central lagoon generally around 2 m deep. A seaward sand ridge occurs at its northern end, up to 18 m wide with coconuts, *Tournefortia*, *Sesuvium* and a typical strand vegetation. *Rhizophora* has established in places on the eastern margin of this sand ridge which shows evidence of erosion and retreat westwards (Stoddart et al., 1982, p.49). Hurricane Hattie caused destruction of mangrove on Tobacco Range; death of a zone of mangrove up to 100 m wide is indicated by standing dead trees seen on several visits to the Range in a zone behind the ridge that has been colonised by *Batis maritima.*

Twin Cays, also called Water Range, has been the subject of detailed studies. It is 1.4 km long and 1.1 km wide and comprises two islands separated by a meandering creek. Apart from small sandy sections at the southern end, this comprises two prominent mangrove islands separated by a meandering central creek. The mangrove vegetation was mapped in 5 classes by Woodrofffe (1995): *Rhizophora* woodland (>4m tall), *Rhizophora* thicket (2–4 m tall), *Rhizophora* scrub (<2 m tall), *Avicennia* woodland, and *Avicennia* open woodland with *Rhizophora*. Unvegetated flats, or poorly vegetated areas, persist on both Twin Cays and Tobacco Range. Taller *Rhizophora* dominates much of the perimeter of the ranges, with *Rhizophora* thicket the most widespread of the vegetation types. *Rhizophora* scrub is frequently found in the interior of ranges, often adjacent to unvegetated flats, but there are exceptions where the margin of the range has been eroded and scrub occurs next to open water. On the eastern margin of Tobacco Range there are locations where *Avicennia* woodland is exposed on the edge of the island, evidently as a consequence of erosion of the shoreline and the underlying peat (Woodroffe, 1995, p. 5). Buttonwood Cay has extensive *Conocarpus erectus* with well-developed coconuts in the middle, surrounded by mangrove, primarily *Rhizophora*.

Particularly noteworthy are the cays of the Port Honduras Bight between Punta Gorda and Punta Ycacos. The Snake Cays represent complex islands, termed moat islands by Stoddart. They lie on reef platforms that rise from lagoon depths of 20–30 m. Within the Snake group there are islands composed of a windward shingle ridge and leeward sand cay, with mangrove covering varying extends within the interior. East Snake Cay, only 260 m long, consists of a densely vegetated sand cay (dominated by coconuts and *Coccoloba*, *Cordia, Terminalia* and *Thrinax*) entirely surrounded by shingle ridges, enclosing a moat and mangroves (Stoddart et al., 1982). West Snake Cay has a shingle rampart on its eastern, windward margin; this is about 370 m long and rises to 1 m above sea level. A moat behind the ridge is about 100 m wide and 0.6 m deep. The mangrove area comprises *Rhizophora mangle*, *Avicennia germinans* and the fern *Acrostichum aureum*, with *Rhizophora* seedlings also in the moat. The sand cay supports coconuts, but also with *Coccoloba* and *Tournefortia*. South Snake Cay is similar but the shingle rampart which is 20 m wide adjoins the sand cay at each end, meaning that the moat is entirely enclosed. Stoddart's explanation for the complexity of these islands was that they were in a deeper section of the lagoon where wave energy was sufficient to move coarser material and construct the shingle ridges on the windward sides of reef platforms.

Stratigraphy of the islands provides further insights into their formation. The broad pattern of Holocene sedimentation across the Belize shelf was revealed by seismic studies and preliminary drilling by Purdy (974). He indicated that there was Holocene sediment beneath Tobacco Range, and that there was 25 m of Holocene above terrestrial sediments at East Snake Cay. Detailed stratigraphy of Tobacco Range and Twin Cays has been described by Macintyre et al. (1995, 2004). The peat accumulation at these sites have been considered to track sea-level rise in this region (McKee and Faulkner, 2000; Mckee et al., 2007). Mangrove peat has been encountered at the base of numerous cores through Holocene sediments across the Belize barrier reef (Shinn et al., 1982). At Boo Bee Patch reef, just south of these mangrove ranges, a Pleistocene patch reef, upon which the Holocene patch reef now occurs, is surrounded by peat presumed to be of mangrove origin, radiocarbon dated to about 8000 years ago (Halley et al., 1977). Stoddart suggested that mangrove ranges may also be located over Pleistocene topographic highs (Stoddart et al, 1982).

Revisiting many of the islands and resurveying them enabled Stoddart to comment on the general pattern of topographic change. He noted that, of 24 islands mapped in 1960–1961 and again in 1972, 11 had decreased in area and 13 increased, with the aggregated area reducing from 35.7 to 33.3 ha The greatest proportion of change was most marked on the smallest islands (Stoddart et al., 1982). Four modes of change were noted: i) catastrophic change resulting from hurricane damage (particularly Hurricane Hattie), ii) marginal erosion, presumably from such storms, iii) reworking of small islets, especially shingle deposits on windward margins, and iv) accumulation of spits and other ephemeral features.

In mapping the mangrove vegetation of Tobacco Range, Twin Cays and Blue Ground Range in 1987, and comparing the ground traverses with aerial photographs of these mangrove ranges taken in 1975, Woodroffe (1995) noted several changes, particularly i) the growth of *Batis* over areas mapped as unvegetated flat, ii) regrowth of *Rhizophora* over areas mapped as unvegetated flat, and iii) localised dieback of *Avicennia*. Storms have left a legacy in these mangrove ranges. A large area of mangrove was devastated at the southern end of Tobacco Range by Hurricane Hattie (Stoddart et al., 1982). Woodroffe (1995) reported erosion around parts of the perimeter of each mangrove range visited in the central barrier reef, indicating gradual contraction of these islands, further confirmed by the greater extent of peat beyond the vegetated shoreline of each island. The numerous stumps of *Avicennia* seen across much of each range, but particularly in association with the unvegetated flats, appear to have resulted from past hurricanes, many perhaps due to Hurricane Hattie.

LOW WOODED ISLANDS ON THE GREAT BARRIER REEF

In contrast to the cays of Belize which had received little description prior to 1959–1960 University of Cambridge expedition, the low wooded islands on the Great Barrier Reef had been the

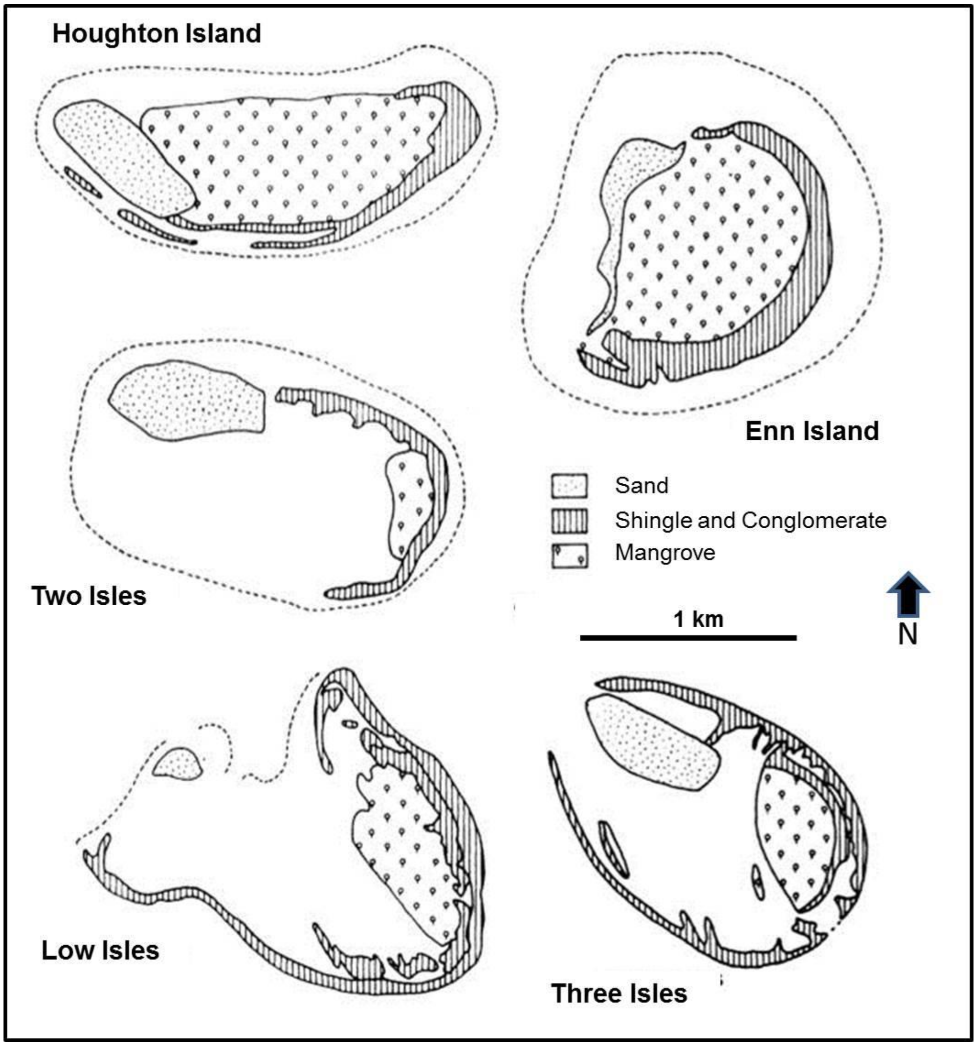

Figure 3. Examples of 'low wooded islands' on the Great Barrier Reef (after Stoddart, 1965).

subject of several notable previous studies. Steers (1929), reporting on the 1928 expedition, described the low wooded islands. The term in general use on Admiralty charts referred to a reef platform on which there were two types of island, a leeward sand cay like those elsewhere on the reef, and what Steers called a mangrove-shingle island (Figure 3).

For Low Isles it could justifiably be said that 'no coral island in the world has been so intensively studied over so long a time' (Stoddart et al., 1978a, p. 63; Hamylton, 2017). Since being sighted by James Cook on the Endeavour in 1770, it was mentioned by King in 1819 and MacGillivray on the *Rattlesnake* in 1848. It had been the base for the year-long Royal Society expedition led by Sir Maurice Yonge in 1928–1929, and Steers (1929) provided a description based on a physiographical map by E.C. Marchant. The oval sand cay to the northwest, vegetated with *Tournefortia, Scaevola, Casuarina* and *Ipomoea*, he likened to sand cays elsewhere, and contrasted this with the shingle ridge that formed the basis of the mangrove-shingle island (or islands in the case of Three Isles). Landward-dipping bedding of the shingle was noted, and erosion along the windward (eastern) margin had resulted in what he then called 'basset edges'. Shingle tongues occurred on the inner side, in places with a shallow moat, and elsewhere with mangroves (Steers, 1929). The mangrove was extensive, dissected by openings and areas of dead mangrove and underlain by a dark mud, adjacent to which is what he termed the pseudo-lagoon, a shallow region, drying over much of its surface at low tide with some corals and *Tridacna* clams. Steers recognised that 'the mangroves are rapidly colonizing these lagoons, and at high water the advancing line of vegetation presents a very striking picture' (Steers, 1929, p.254). He also commented on the case of one of the Turtle group where the mangrove was continuous from the shingle to the sand cay and the pseudo-lagoon was absent, which he postulated might be due to the initial size of the reef platform on which the islands had developed. Steers was less clear about the formation of the mangrove-shingle island and whether it was of the same age as the sand cay, or whether sand cay formation preceded development of the mangroves, which subsequently obstructed the delivery of skeletal reef material to the cay.

A particularly detailed map of Low Isles was prepared by Spender through triangulation with a theodolite. Spender considered that

> 'There is more than a temptation to take it as self-evident that the island-reefs [his term for low wooded islands] of the Queensland coast tend to develop towards an island where mangroves cover the entire space between the rampart and the cay……But the evidence of the reefs I take to be otherwise. The relics of previous movements seen in the sand-rock, conglomerates, and occasional dead or dying mangroves, the limits of the mangrove-swamp, and also the historical evidence, all suggest that the islands have existed long enough to find an equilibrium of the elements on the reef, about which distribution alternate growth and destruction make small oscillations' (Spender, 1930, p. 290).

Spender saw the islands as having reached a 'comparatively stable and balanced finality'. He commented on apparent loss of mangrove from a shingle tongue at the south of the reef, where there were then a few battered and ancient *Rhizophora* trees. Stoddart commented that this had in 1973 many young recently established mangroves. Comparison of 1928 and 1945 aerial photographs indicated that patches of mangrove had been expanding and coalescing, and for Fairbridge and Teichert (1948), in comparison with Bewick Island, Houghton Islands and Low Wooded Island itself, it seemed 'it would only be a question of time until most of the Reef Flat would be covered with dense mangrove growth'.

A further reconnaissance of 27 islands in 1936 enabled Steers and Kemp (1937) to consider the processes of formation of low wooded islands. Low Isles represented the southernmost of these islands but was not necessarily typical, others containing mangrove coverage of differing proportions of the reef platform, in some cases with no lagoon present. All occurred where the outer reef was relatively close to the mainland in contrast to further south on the Great Barrier Reef. In reassessing his earlier discussion of the formation of low wooded islands, Steers drew attention to an unnamed island in the Turtle group where a sand cay and shingle ridge are accumulating contemporaneously. Although shingle ramparts here did not appear to have thwarted cay accretion, he speculated that further consolidation of the shingle ridges would ultimately starve the cay of sand. Storms were realised to punctuate development, at least until beachrock cementation and denser vegetation gave the cay greater stability. Spender hypothesised a cycle, implying that the islands were in equilibrium. Steers preferred a view that a prominent platform on the islands and on much of the Queensland coast recorded a higher sea level and that the bassett edges dated from this time. He felt that the extent of mangrove on individual reefs varied in size partly according to the area of the reef, but also fortuitously in relation to a variety of factors such as the supply of seedlings and tidal conditions. Given time mangroves could cover the reef top and also enclose the cay (Steers and Kemp, 1937, p133). Observations of the 1934 cyclone and its effect on Low Isles were also summarised by Steers and Kemp (1937), but had been described in detail by Moorhouse (1936).

The Royal Society and Universities of Queensland Expedition to the northern Great Barrier Reef took place from mid-July to mid-November in 1973, led by David Stoddart. It comprised three phases, examining the reef and reef islands between 11° 30′ S and 17° S and its primary purpose was to understand recent reef history and its response to Holocene sea-level change, and included a range of methodologies such as shallow coring, geophysical surveys, analysis of reef and inter-reef sediments, composition of modern reef communities, as well as an analysis of the geology and geomorphology of reef islands (Stoddart, 1978).

The expedition conclusively demonstrated that this region of northern Queensland had experienced a higher sea level in mid Holocene and that this had had a major influence on the geomorphology of the reef islands (McLean et al., 1978). Since the cessation of upward reef growth, reef flats had developed on the reef platforms of the northern Great Barrier Reef (Stoddart et al., 1978b). The reefs were formed over a Pleistocene topography; Pleistocene limestones were encountered at depths as shallow as 4 m below low water springs in coring on Bewick (Thom et al., 1978), and it was concluded that:

> 'variation in the depth of the Pleistocene-Holocene disconformity may strongly influence the degree of development of patch reefs and associated cay and mangrove cover. Well-developed 'low wooded islands' (e.g. Bewick) could possess a shallow Holocene reef cap compared with reefs which contain little or no cay development' (Thom et al., 1978, p. 52).

During the expedition, 67 reef islands were mapped by Stoddart; each was surveyed using pace and compass, except Low Isles, which was re-surveyed using a tape and compass to enable more precise comparison with the earlier map of Spender. There have been various attempts to classify reef islands on the Great Barrier Reef, adopting criteria such as sediment type, island location, island shape, or stage of vegetation cover (Hopley, 1982). Stoddart and Steers (1977) advocated a classification that recognised, sand cay, vegetated or unvegetated; sand cay with shingle, generally vegetated; shingle cay, vegetated or unvegetated; mangrove cay; mangrove cay with windward ridge; low wooded island; and emergent limestone island. However, Stoddart et al. (1978b) classified islands studied on the expedition as either unvegetated sand cays, vegetated sand cays, or low wooded islands, if supplied with sufficient sediment, cays were considered to 'mature' from a simple sand cay to developing ramparts and mangrove forests towards an end stage when the platform is covered in vegetation (Stoddart et al., 1978b).

Low wooded islands received particular attention during the expedition. Features characteristic of these islands included an extensive reef flat, ramparts on the windward eastern margin, a 'promenade' of higher conglomerate, partially-lithified shingle deposits, in places standing up from the reef flat as bassett edges where the forests from past storm deposits had been truncated on their windward margin, sand cays on the leeward margin sometimes with adjacent boulder zones, and a mangrove cover of variable extent. Based on these characteristics, Stoddart et al. (1978b) differentiated three types of low wooded island. In the first, on large reef flats, mangroves were of limited extent and the sand cay is distinctly separate (e.g. Lowrie, Two Isles, Three Isles, Pipon, Chapman, Watson and West Hope). In the second, mangroves are more extensive joining the shingle ramparts and the sand cay, such as on Bewick where the entire platform is covered with mangroves, or Newton and Nymph. The third type is typical of the Turtle group which lack a central open flat, but have shingle and mangrove wrapped around the sand cay, whereas a further category is miscellaneous and covers islands not in the previous classes, such as Hampton and Pethebridge Islands.

The resurvey of Low Isles enabled a comparison of change over the 45 years since the detailed mapping by Spender (Stoddart et al., 1978a). Substantial alteration was observed in the size and location of the shingle ramparts which had affected coral growth on the reef flat. Mangroves were observed to have spread considerably at Low Isles, but not to the same extent at Three Isles, which was also mapped both in 1929 and 1973, although not to the same precision. Steers realised that the extent of mangrove on a low wooded island was a function of the development of ramparts. He appeared to consider that ramparts were built by regular wave processes; however the importance of storms was demonstrated by the observations of Moorhouse (1936), who recorded a fresh rampart deposited by the 1931 tropical cyclone, and its reworking landward by the 1934 cyclone. Steers considered that the ramparts were the consequence of former higher sea levels. Whereas the 1973 expedition provided unequivocal support for a sea level higher than present, for which radiocarbon dating of fossil microatolls on many of the reef platforms was particularly convincing evidence, it became apparent that the deposition of ramparts of coarse material by storms occurs episodically on these platforms, and is not directly related to the level of the sea. Fairbridge and Teichert had undertaken a full re-analysis of the ramparts on Low Isles in 1945 (Fairbridge and Teichert, 1948). They identified four ramparts. The first, innermost one was represented by shingle tongues mapped by Spender within the mangroves; their second was equivalent to Spender's inner rampart; the third corresponded to Spender's outer rampart; and their fourth included what was fresh shingle in 1929 but which had had material added by the storm of 1931. Whereas the inner ramparts had not moved in 16 years, the more eastern ramparts did show evidence of reworking landwards. Loose shingle was not obvious when examined in 1954 (Stephenson et al., 1958), and the location of shingle ramparts was typically characterised by bassett edges in 1973 (Stoddart et al., 1978a, p68).

Earlier mapping of Low Isles had mapped the mangrove swamp, an area predominantly of *Rhizophora stylosa* (initially called *R. mucronata*) up to 20 m tall, and a more open area or mangrove park of saplings and isolated trees. The mangrove was observed to have been damaged in the storms of 1931 and 1934, but had recovered by 1945 according to Fairbridge and Teichert (1948). Low Isles was visited briefly by Macnae in 1965 who thought there was little evidence of mangrove expansion (Macnae 1966). There was evidence that patches of *Rhizophora* had been expanding and coalescing throughout the mangrove park (Figure 4). The margin of the mangrove swamp seemed less changeable, except where young *Rhizophora* were expanding at its northern side, causing Fairbridge and Teichert (1948) to say that it would only be a question of time before the entire reef flat would be covered with mangrove as had already occurred on Bewick, and Houghton or Low Wooded Island. However, the detailed mapping by Stoddart in 1973 confirms an overall trend of extension, indicating that mangrove cover of 21.9 ha in 1929 had extended to 36.5 ha in 1973 (Stoddart et al., 1978b). Comparison of mangrove extent shown on subsequent aerial photographs was undertaken by Frank and Jell (2006); their mapping showed both extension of mangroves onto the ramparts, but also gradual advance of the western margin across the reef flat.

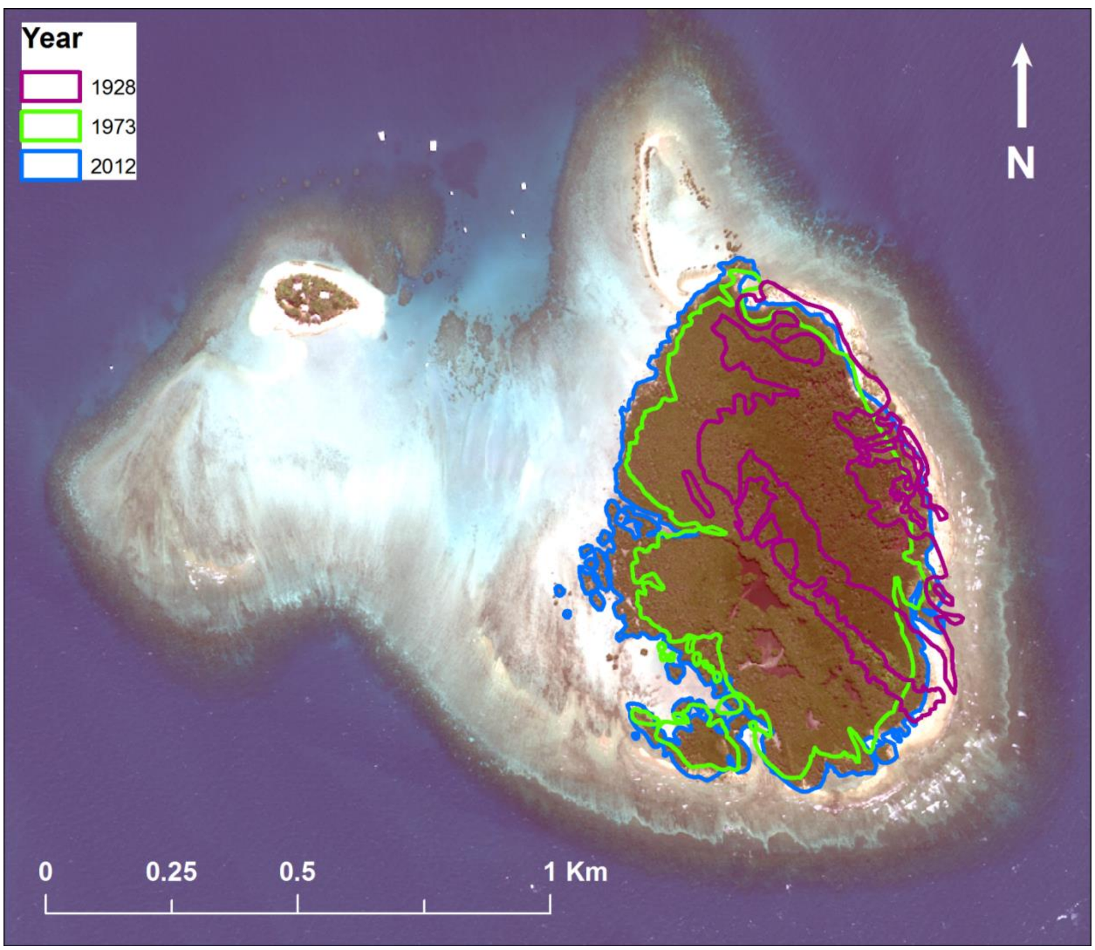

Figure 4. The extent of the mangroves that comprise Woody Island at Low Isles (Great Barrier Reef) in 1928, 1973 and 2012. Outlines are digitised at a scale of 1:500 from the maps produced by M.A Spender during the 1928–1929 *Great Barrier Reef Expedition* by theodolite triangulation with reference to the first

aerial photographs of Low Isles (purple line) and by D.R. Stoddart during the 1973 Royal Society and Universities of Queensland Expedition to the Northern Great Barrier Reef (green line). Outlines are overlayed onto a WorldView-2 satellite image of Low Isles acquired in 2012 (after Hamylton, 2017).

A general pattern of progressive change is implied by these results. It is not as regular or predictable as Spender or Steers inferred. Low Isles is perhaps not typical of other low wooded islands; it lacks the high promenade, an erosional surface characteristic of the conglomerate of lithified ramparts seen on other low wooded islands. A schematic cross-section of a reef flat on a low wooded island, and the distribution of mangroves across it, is illustrated by Thom, based on fieldwork during 1973 at Bewick (Thom, 1975, p. 475). Mangroves do progressively extend on some reef flats, but it seems likely that this is episodic (Stoddart et al., 1978c). Stoddart addressed this specifically in a synthesis paper on mangroves (Stoddart, 1980). Although not all the maps of individual reef islands were published in the 1978 monograph of the Royal Society, the distribution of mangroves on 21 reefs was analysed in this synthesis. He concluded that the area and spread of mangroves was a function of reef morphology. The most extensive mangrove is *Rhizophora stylosa* which composes most of the mangrove swamp and mangrove park (the more open areas) over reef flats on the islands, generally up to 15 m tall. Several other mangrove genera are associated with ramparts, in particular *Avicennia marina*, *Aegialitis annulata, Excoecaria agallocha* and *Osbornia octodonta*. The Rhizophoraceous mangroves *Bruguiera* spp. and *Ceriops* spp are reasonably widespread, replacing *Rhizophora* in the leeward of shingle ramparts on the larger low wooded islands. However, *Sonneratia alba* is not particularly abundant in this reef setting although forming distinct communities on the seaward margin of mangrove forests on the mainland. *Aegiceras corniculatum*, *Lumnitzera racemosa* and *Xylocarpus granatum* were each recorded from only one island. In contrast to the broader suite of plants that colonise small islands, the diversity of mangroves does not show a relationship to area, but it appears that the establishment of mangroves other than *Rhizophora* is opportunistic on any reef platform.

Many of the observations of change associated with the shingle ramparts have also had implications for mangroves. Changes to the sand cay were also recorded by the successive mapping. Expansion of *Avicennia* on ramparts was observed by Fairbridge and Teichert (1948). In places reworking of the shingle has resulted in localised mangrove occurrence on the windward, eastern flank of the rampart. Stoddart (1980) noted that mangroves were extensive where there was fossil reef formed 5–6,000 years ago. Fossil microatolls indicated that the reef top had reached its vertical limit, and the association of mangroves with these areas, implied that mangrove extent might be a function of the maturity of the reef top, with less mangrove on those reefs where parts of the reef top had not reached this upper threshold. In this sense, Stoddart (1980) considered these mangroves geomorphologically opportunistic in a similar way to the mangrove communities associated with the landforms of deltas and estuaries, described by Thom (Thom, 1967; Thom et al., 1975). The presence of honeycombed rock around the mangrove park on Low Isles has been noted by previous researchers; Spender had seen dead corals amongst the mangroves, and Fairbridge and Teichert (1948) had hypothesised that mangroves might promote the dissolution of calcareous substrate.

An issue that remained a subject of debate was the relative timing of sand cay deposition, shingle rampart formation, and mangrove forest distribution. Earlier researchers had inferred that sand cays were more likely to be formed on the leeward of these platforms before there were well-developed ramparts on the windward or mangrove forests covering substantial proportions of the reef top. Radiocarbon ages of sediments indicated two modal times of island building, >3,500 years BP and ~1,500 years BP, and it was considered that sand cays had begun to form after about 4000 years BP (McLean and Stoddart, 1978). Where there are extensive mangroves on a reef top, there are limited areas for calcareous sediment production, and restricted fetch for wave transport of sediments. Recent investigations on Bewick, which is almost entirely covered by mangroves, indicates further support for initiation of the sand cay around 4,000 years ago and subsequent stability, but the timing of rampart formation and mangrove spread on this reef remains unclear (Kench et al., 2012).

DISCUSSION

The differing extent of mangroves on adjacent reef platforms in both Belize and on the Great Barrier Reef, as well as on other reefs in the tropics, poses the challenge of explaining the environmental constraints under which these systems have developed. Observations and inferences by Stoddart address many of the key factors, and will be considered below.

The Physiographic Approach

Studies of reef islands by Steers and Stoddart were classic examples of the physiographic approach. *Physiography* is often considered synonymous with physical geography; it is defined as a subfield of geography that studies physical patterns and processes on the Earth. However, it is an essentially field-based and practical approach to understanding nature. T.H. Huxley, in the preface to his book entitled *Physiography* (Huxley, 1878) was emphatic to differentiate physiography from 'latitudes and longitudes; the heights of mountains; depths of seas; or the geographical distribution of kangaroos and *Compositae*'. Instead he indicated the need to focus on 'place in nature', and to show the application of 'the plainest and simplest processes of reasoning to any one of these phenomena... to show, lying behind it, a cause, which again suggests another; until, step by step, the conviction dawns upon the learner that, to attain to even an elementary conception of what goes on in his parish, he must know something about the universe; that the pebble he kicks aside would not be what it is and where it is, unless a particular chapter in earth's history, finished untold ages ago, had been exactly what it was' (Huxley, 1878, p. vii – viii). Physiography was also practiced by many of the great North American geoscientists, including John Wesley Powell, Nathaniel S. Shaler and William Morris Davis.

Whereas Huxley was writing a textbook and hence illustrated physiography with a local example likely to be familiar with his readers, namely the Thames as it flowed through parishes in London, Steers and Stoddart, based in the Department of Geography at the University of Cambridge, set out across the world to examine coral reefs, ecosystems that had exerted such a profound influence on Charles Darwin. Much of their science was undertaken during expeditions, and built directly on the close observation and surveying techniques that characterised the navigators, such as Richard Owen, who had gone before them. Detailed mapping, often meticulously undertaken by pace and compass, provided one of the principal sets of data, for, as Stoddart often propounded, a limitless set of further measurements could be derived from an adequate map. On the dynamically changing backdrop of a coral reef, geomorphological processes were continuing to reshape the surface morphology, and the present state was often but a fleetingly ephemeral stage in the most recent chapter of earth's history. Nevertheless, each reef appeared to have undergone its individual journey, partially inherited from underlying topography, constrained by changes of sea level and perturbations from occasionally catastrophic storm impacts.

Sea-Level Changes and Their Legacy

In 1974, Purdy demonstrated both by coring and seismic traverses across the Belize barrier reef, the significance of inheritance from the antecedent topography of the Pleistocene surface. In some cases, modern reefs were underlain by constructional features associated with the Last Interglacial, but elsewhere such topography was enhanced through karstification during glacial phases (Purdy, 1974). Stoddart had already realised that sea-level changes might be significant, and that underlying topography may be inherited. For example, in describing the north-south alignment of mangrove ranges within the Turneffe lagoon, such as Crayfish Range, he suggested that there might be a bedrock core, or old patch reefs before the eastern rim adopted its present form (Stoddart, 1962a). He commented that the Phillips Petroleum Company was in 1961–1962 drilling a test well west of the northern end of Tobacco Range and recognised the potential insights into shelf structure this could provide (Stoddart, 1963, p. 52). Purdy dated peat around 8000 years BP from depths of >20m on the outer Belize barrier reef, and subsequent work has further documented the most recent rise of sea level over this period (Monacci et al., 2009).

Stratigraphic studies on these isolated carbonate platforms have subsequently revealed their broad sedimentary history (Gischler, 1994; Gischler and Lomando, 2000). 17 vibrocores from within the lagoon of Turneffe Islands penetrating more than 5 m into the sediments, indicated a Late Quaternary sedimentary sequence of Pleistocene bedrock, overlain by a shallow soil, then a mangrove peat, culminating in carbonate lagoon sediments dominated by *Halimeda* but also with shell beds of *Codakia orbicularis*. Calcareous sediments have a dark brown humic stain from decaying organic matter (Gischler and Lomando, 1999). The thin soil that veneers the Pleistocene limestone contains plant roots on which a radiocarbon age of 7290±90 years BP has been obtained. This is overlain by peat derived from the mangroves, within which are reddish roots of *Rhizophora*, and also traces of pneumatophores of *Avicennia*; ages of 5610±80 years BP were derived near the base, with ages of ~4000 and ~2000 years BP at shallower depths (Gischler, 2003). Mangrove peat, formed as Chapman realised in areas where there was limited or no supply of terrigenous sediment, and only slow accretion of calcareous reef sediments, reaches its greatest thicknesses where sea-level rise has provided sufficient accommodation space. It has become an important source of paleo-environmental data for the reconstruction of late Holocene sea-level adjustments in this region (Scholl, 1964; Woodroffe, 1981; Hendry and Digerfeldt, 1989).

An inferred evolution of Turneffe indicates that a saucer-shaped limestone island was inundated by the rising sea level, which eventually breached the peripheral bedrock rim. Mangroves flourished in the protected centre of the platform, with average sedimentation rates of 0.82 m per thousand years (up to a maximum of 1.23 m per thousand years) interpreted from the cores. Pollen analysis confirms the prominence of *Rhizophora*, though in one specific core indicating it was replaced by *Salicornia* around 4000 years ago (Wooller et al., 2009). Open marine conditions typical of Lighthouse and Glovers Reefs did not develop on Turneffe due to the high bedrock elevation implied by the shallow depth to Pleistocene near the perimeter, and its protected nature in the lee of Lighthouse Reef (Gischler, 2003; Gischler and Hudson, 2004).

In describing the mangrove-sand islands of Turneffe, primarily those along the eastern rim, Stoddart realised that the beach ridge was relict in places, because mangroves had established on the reef flat to the east of it. Whereas Vermeer attributed this to a higher sea level, also inferring that other features along the Belize coastline had formed when the sea was higher, Stoddart dismissed this. Stoddart had observed evidence for higher sea level during the mid Holocene from Australia, but was able to reconcile this with the absence of such a highstand in the West Indies as proposed by Adey (1978) and others.

Radiocarbon ages from Turneffe are broadly consistent with the regional sea-level curve derived using a compilation of dates on coral and mangrove remains from throughout the Caribbean, including numerous samples from thick sections of mangrove peat from Tobacco Range and Twin Cays, Belize (Toscano and Macintyre, 2003). Several researchers have suggested that the decelerating pattern of sea-level rise experienced in Belize differs from that for adjacent parts of the Caribbean (Westphall, 1986; Woodroffe, 1988; Gischler and Hudson, 2004; Monacci et al., 2009). Gischler (2006) considered that the Belize data, including basal mangrove peats from Turneffe at 5.3 m below sea level returning ages of 6,395, and 2.8 m from beneath an island returning an age of 6,180, demonstrated a sea level only ~3 m below present 6000 years ago. By contrast, Toscano et al. (2018) have shown that there appears to have been little if any compaction of mangrove peats. The pattern of isostatic adjustment across the Caribbean remains unclear; it seems likely that no single pattern of sea-level rise can be used for the entire region (Milne and Peros, 2013; Khan et al., 2017), and further work will be needed to clarify site-specific relative sea-level history.

On the Great Barrier Reef, the 1973 expedition reported conclusive evidence that sea level had reached a level close to present in mid Holocene, and had been above present for much of the past few millennia. Particularly convincing was the record from fossil coral microatolls (Mclean et al., 1978). Subsequent survey and dating of fossil *Porites* microatolls from along the mainland coast of Queensland by Chappell (1983), derived a record that appeared to show sea level gradually falling smoothly over the past 6000 years from the highstand to present. Nevertheless, there remains debate about whether there may have been oscillations during this period of sea-level fall (Lewis et al., 2008). Evidence from fixed biological indicators (Baker and Haworth, 2000), and that from foraminifera (Woodroffe, 2009), suggest there may have been oscillations, but this conflicts with the evidence from microatolls (Lewis et al., 2013). Mangroves do not have a substrate of peat beneath them because the falling sea level has meant little accommodation space for mangrove establishment. Frank and Jell (2006) found only 10–15 cm of organic mud beneath mangroves, which in places were extending over a coral breccia. Thom (1975) reports that depths may be up to 1 metre, and Marshall and Orr (1931) recorded 4 m of black mud and calcareous sediment from the reef flat of Low Isles. By contrast deeper buried mangrove sediments in the lagoon do record the final stages of postglacial sea-level rise, culminating in the highstand (Grindrod and Rhodes, 1984). The successional stages to which Stoddart referred in his 1980 paper, were inferred to reflect the varying elevation of the reef flat as a consequence of the irregular topography as the reefs grew to reach the constraining sea level, and hence the extent of mangrove covering this reef flat varied as a function of the maturity of the reef platform and the morphodynamic processes that enable mangrove establishment (Stoddart, 1980). These could be highly individual, reflecting for example the emplacement of a shingle ridge by a cyclone, or its breaching by a subsequent storm. Mangroves might opportunistically establish contingent on a reef's past history and subsequent perturbations.

Mangrove is more extensive on islands in Torres Strait than it is in the northern Great Barrier Reef. Here there are islands that are almost entirely mangrove, such as Sassie. At least 35 species of mangrove occur, and no single island has all species on it. Although none of the islands in the Strait are classified as low wooded islands, the reef flats are also known to have developed as a consequence of a mid-Holocene higher sea level (Woodroffe et al., 2000). Emergent microatolls recording this higher sea level occur within mangroves, for example on Yam Island (called Iama, locally). Recent mapping based on aerial photographs from 1974, 1987, 1998 and 2011 has documented expansion of mangroves on this island. On Yam, mangroves covered 67.9 ha in 1974, 64 ha in 1987, 75 ha in 1998 and 78.5 ha in 2011 (Duke et al., 2015). There has been local loss, partly as a result of clearing associated with runway construction during the period of record, however, extension was seen across the reef flat where fossil microatolls provide local microtopographic irregularities which favour sporadic mud accumulation adjacent to such fossil corals. Expansion of mangroves has also been notable on Darnley (Erub) Island, where it is attributed to sedimentation on the reef flat as a result of hillslope erosion on the volcanic island, making further areas of the reef flat suitable for mangrove colonisation (Duke et al., 2015).

The Role of Hurricanes

Stoddart identified the importance of hurricanes in shaping the reef islands of Belize. He observed evidence of damage to mangroves which he attributed to storms in his 1962 monograph, before witnessing the impact of Hurricane Hattie. The recurrence of storms is recognised as shaping outer cays such as Dogflea Cays on Turneffe (Murray et al., 1999). An unnamed hurricane in 1931 virtually destroyed Belize City, killing over 1000 people. Hurricane Hattie (1961), whose devastation of the coastal ecosystems has been documented (Vermeer, 1963; Stoddart, 1962b, 1963, 1969), led to the relocation of the capital city further inland. Subsequent storms, such as Mitch in 1999 and Keith in 2000 have had further impacts (Murray et al., 1999). McCloskey and Liu (2013) speculated on the phases of carbonate sedimentation within the mangrove peat in several cores; because peat clasts apparently originated from eroded mangrove areas and were deposited contemporaneously within carbonate layers, they considered this indicated high-energy events, perhaps even tsunami.

Mapping of the mangroves of Turneffe has been undertaken as part of broader ecological studies in the western Caribbean, adopting the structural categories recognised by Lugo and Snedaker (1974). Turneffe accounted for 7420 ha of mangrove, 9.4% of the national total for Belize, comprising 3875 ha of dwarf, 3355 ha of medium and 190 ha of tall forest (Murray et al., 2003). 17.3 ha have been altered by anthropogenic effects, primarily fishing camps. The fringing red mangroves (*Rhizophora mangle*) occur at the lowest levels in the tidal frame, transitioning into *Avicennia germinans* at slightly higher elevation with *Laguncularia racemosa* forming further inland. Dwarf *Rhizophora* forests have developed in areas of higher salinity (Meerman, 2006). Clearing of land in these mangrove islands is contributing further to the erosion that is occurring (McKee and Vervaeke, 2009).

In a much more recent study of Turneffe Islands, Chi (2012) has reiterated the important role that hurricanes play, recording that the reef platform had experienced 6 hurricanes and 4 tropical storms in the 157 years from 1851 to 2008. In addition to historical photographs (including access to those taken by David Stoddart) before and after Hurricane Hattie, Chi examined more recent imagery, recording a 26% loss of vegetated cays between 1945 and 2008 for the northern group of Cockroach Cays, and Calabash Cays (Chi, 2012, p. 90). During this time 4 new cays with less than 0.1 ha formed in the same area. Storms re-activate the ridge along the margin of islands on the eastern rim, reworking sediments onto the prop roots of *Rhizophora*. In places, carbonate layers within the mangrove peat were attributed to storms. Movement of cays on the eastern margin could be detected, averaging 18 m to the west, though the centroid of Deadman Cay shifted 43 m westward between 1945 and 2006 . Hurricane Keith (a category 3 hurricane) killed mangrove in the leeward along the Cockroach Cays, but extensive layers of mangrove peat survived erosion or burial. In the 8 years following that storm, mangroves revegetated nearly all of the areas damaged by that storm, probably because trees that survived in the lee of the ridge provided propagules for re-establishment. However, in some areas that had previously been dominated by *Rhizophora*, these were now colonised by *Avicennia* with a ground cover of *Batis maritima*.

These observations reinforce the view that mangroves promoted cay development by stabilising substrate and trapping sediment. Areas of sand planted to coconut were completely stripped of vegetation. Chi revisited three cays in the Cockroach group over a 5-year period to observe the rate of re-foliation, vegetative regrowth and seedling establishment. Also Soldier Cay was visited two weeks after the passage of Hurricane Ivan in 2004; the principal effects of this seemed to be the overwashing of coral rubble into mangroves, with 50 cm of new material deposited within the mangroves (Chi, 2012, p. 110). Chi showed that areas of mangrove that had been covered with seemingly dead mangrove in 2003 (e.g. the centre of Cockroach Cay-22) had been largely re-colonised by 2008 (Chi, 2012, p. 107). Most cays on the eastern margin of Turneffe reformed in their original locations; *Rhizophora* extended preferentially on the western side of cays. Material may be moved into mangrove forests on the windward margin, but Macintyre et al. (1987) found little sediment carried more than 150 m in from the reef crest on Tobacco Reef in Belize.

Cyclone history has also played a role in the case of Low Isles. Mangroves were severely damaged by the cyclone that hit the reef in 1934, and this led to temporary reversal in the otherwise expanding mangrove area on the reef flat. At Low Isles, further changes have occurred since the 1973 mapping by Stoddart. Rasmussen (1986) recorded further adjustments to the ramparts, including a breach into the mangrove swamp at the very southernmost part of the reef platform. She commented that ‘it is obvious that initial accumulation of shingle and rampart formations are created during episodic cyclonic events. However, continuing pattern of shingle redistribution takes place under normal weather conditions’ (Rasmussen, 1986). The mangrove swamp and mangrove park increased by 75% from 1929 to 1986, reflecting in her view both a supply of sediment and of nutrients, the latter related to land use change on the mainland. Frank and Jell (2006) recorded further increase up to 2001.

The individual history of reef tops varies both between platforms on the Great Barrier Reef, and in relation to other reef areas in the region. For example, Spender recognised that differences between Australian low wooded islands (termed island reefs by the 1928 expedition members) and those in Jakarta Bay, Indonesia; the former were on solid reef flat substrate, whereas the latter were on unconsolidated muds, hence their lagoon was less constrained by inheritance form previous morphology. He considered that each had reached, for a given form of the reef and weather conditions, a comparatively stable and balanced finality (Spender, 1930).

The availability of satellite imagery provides much easier access to aerial views of the extent of mangroves on reefs around the world (Figure 4). Broad patterns of change can be examined comparing the field-based maps made by David Stoddart and imagery available on Google Earth. On many low wooded islands, there appears to have been little change in the extent of mangroves, for example Two Isles, Three Isles, and Low Wooded Island. Bewick appears to have reached a stage where there is no longer available space on the reef top for any further mangrove expansion. Mangrove does appear to have continued to increase on Low Isles. Further mangrove appears to have colonised the reef flat as well as infilled pools within the existing forest on Coquet and Hampton. On Chapman it has decreased, whereas on Sinclair-Morris and West Pethebridge, both local increase and loss have occurred.

SUMMARY

David Stoddart was a physiographer of exceptional ability. He participated in a series of expeditions, initially joining a team from Cambridge to examine the islands in British Honduras. His PhD involved detailed descriptions of the atolls that lie east of the Belize barrier reef, and of those, Turneffe contains particularly extensive mangrove forests. Stoddart himself led many such expeditions. I had the good fortune, when I was studying mangroves in the Caymans Islands under his supervision, to participate in the expedition he led to Little Cayman, and there to be guided by him in the investigation of stands of *Rhizophora*, both on the reef flat of Little Cayman, but also in small basins within the limestone island interior. As on the Belize islands, including the mangrove ranges and Turneffe, these mangroves were underlain by mangrove peat, formed largely from the fibrous roots of *Rhizophora*, and they record the final late-Holocene stages of decelerating sea-level rise. The contrasting sea-level history from Belize and Australia explains some of the differences in the morphology and development of the reefs, the mangrove forests, and the adjacent islands when these are formed. Subsequent studies have elucidated the stratigraphy and geochronology in many locations where Stoddart undertook pioneering research; in many cases confirming the hypotheses that he proposed.

However, David Stoddart was always aware of the broader suite of factors, such as inherited topography and morphodynamic feedbacks, that might explain particular sets of circumstances on different reefs. In many cases, mangrove establishment appeared to have been opportunistic, reflecting some contingent event in the past history of that site. His insightful descriptions and meticulous fieldwork have provided a wealth of observational data that have been an incredible inspiration to me, and also many others. His fieldwork followed the fine physiographic traditions adopted by Steers, and to a lesser extent Chapman. He sought to explain nature by knowing it, and was an extremely astute observer. David was always open to alternative hypotheses; he has provided an unparalleled body of scientific observations and he would have wished that these be used by future environmental scientists to test his hypotheses and to generate new ideas.

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